EFFECTS OF MOISTURE ON ACRYLONITRILE BUTADIENE STYRENE (ABS) FILAMENT MATERIAL IN FUSED DEPOSITION MODELING (FDM) RAPID PROTOTYPING MACHINE

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By

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LIST OF ABBREVIATIONS

3DP	3 Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene polymer
C_p	Heat capacity
CAD	Computer Aided Design
CNC	Computer Numerical Control
DDM	Droplet Deposition Manufacturing
DSC	Differential Scanning Calorimetry
FACS	Finned Air Cooling System
FDM	Fused Deposition Modeling
FEA	Finite Element Analysis
FTIR	Fourier Transform Infrared
IR	Infra Red
LOM	Laminated Object Manufacturing
PC-ABS	Poly-carbonate ABS
RP	Rapid Prototyping
RTM	Rapid Tool Making
SGC	Solid Ground Curing
SLA	Stereo Lithography Apparatus
SLS	Selective Laser Sintering
SML	Stratasys Modeling Language
STL	Stereolithography
T_g	Glass transition temperature
TMA	Thermo Mechanical Analysis

LIST OF SYMBOLS

M_t	Mass water sorbed at time t
M_s	Mass sorbed by the polymer at equilibrium
γ	Shear rate
τ	Shear stress
η	Viscosity
ω	Angular frequency
P	Pressure gradient
R	Capillary die of radius R
L	Die length
Q	Volumetric flow rate

KESAN LEMBAPAN TERHADAP FILAMEN AKRILONITRIL BUTADIENA STIRENA (ABS) YANG DIGUNAKAN DALAM MODEL LAKURAN MENDAPAN (FDM) MESIN PEMPROTOTAIPAN PANTAS (RP)

ABSTRAK

Akrilonitril butadiena stirena (ABS) adalah sejenis termoplastik yang menjadi rapuh selepas beberapa bulan atau minggu, apabila terdedah pada lembapan udara. Oleh kerana termoplastik ini bersifat higroskopik, bahan ini tidak dapat digunakan dalam Model Lakuran Mendapan (FDM) apabila terdedah pada lembapan udara. Oleh itu, kajian mengenai kesan kelembapan dalam filamen ABS dijalankan. Eksperimen dijalankan dengan membiarkan ABS filamen pada lembapan untuk suatu waktu tertentu. Selepas dibiarkan untuk suatu tempoh tertentu, kesan lembapan udara pada fizikal, termo mekanikal, reologi, dan struktur molekul perubahan diperhatikan. Diameter dan berat perubahan filamen diukur untuk menilai kesesuaian ABS untuk digunakan dalam FDM liquefier. Perbezaan ukuran berat yang dilakukan untuk melihat keupayaan menyerap lembapan keupayaan penyerapan ABS. Selepas terdedah untuk suatu masa tertentu, filamen diameter ABS meningkat sehingga 3.93% (untuk keadaan sekeliling) dan 1.86% (bagi keadaan lembapan rendah) dari ukuran diameter yang diterima dari pengeluar. Menggunakan DSC, sifat termo-mekanikal dari segi suhu peralihan kaca (Tg) didapati menurun dari masa ke masa dalam semua keadaan alam sekitar. Anjakan suhu ke sebelah kiri dalam data kasar DSC menunjukkan penurunan Tg. FTIR analisis dilakukan untuk melihat kehadiran ikatan O-H akibat penyerapan lembapan. Ikatan O-H wujud akibat serapan lembapan seperti yang ditunjukkan di rantau 3600-3200 cm^{-1}. Reometer kapilari digunakan untuk memerhati tingkah laku aliran lebur ABS. ABS filamen terdedah kepada keadaan basah menunjukkan kelikatan tertinggi (adalah antara 52.6-258 Pa•s) manakala ABS filamen terdedah kepada keadaan kering menunjukkan kelikatan rendah (adalah antara 49.65-212 Pa•s). Berdasarkan simulasi pada FLUENT, profil suhu kekal malar di sepanjang liquefier itu. Kelikatan berkurangan dengan peningkatan tegasan ricih, bersetuju dengan data dari eksperimen kapilari reometri.

Kesimpulannya, lembapan udara menyumbang kepada kerosakan filamen ABS yang akan digunakan dalam FDM. Bukan itu sahaja, sifat haba dan reologi filamen ABS selepas terdedah kepada lembapan merosot teruk menjejaskan kecekapan FDM.

EFFECTS OF MOISTURE ON ACRYLONITRILE BUTADIENE STYRENE (ABS) FILAMENT MATERIAL IN FUSED DEPOSITION MODELING (FDM) RAPID PROTOTYPING (RP) MACHINE

ABSTRACT

Acrylonitrile butadiene styrene (ABS) is a type of thermoplastic that becomes brittle after a few months or even weeks, when left outdoors. Due to its hygroscopic nature, this material gradually degrades and becomes unsuitable for use in Fused Deposition Modeling (FDM). In this work, a study on the effects of moisture in ABS properties is conducted. Experiments were conducted such that filaments were exposed to different types of humidity conditions for a certain amount of time. Experimental test on the effect of moisture on physical, thermo mechanical, rheological, and chemical structure changes were observed. The filaments' diameter and weight changes are measured to assess the ABS's suitability for use in FDM liquefier. Weight difference measurement was done to observe the material's moisture sorption ability. After being exposed for a certain amount of time, the ABS filament diameter increased up to 3.93% (for ambient condition) and 1.86% (for desiccated environment) from its as-received diameter. Using DSC, thermo-mechanical behavior, in terms of glass transition temperature (T_g) was found to decrease over time in all environmental conditions. Raw data curve shifted to the left indicates a decrease in T_g. FTIR analysis was done to observe the presence of O-H bond with moisture absorption by the filament. O-H bond exists with moisture absorption as shown in region 3600-3200 cm^{-1}. Capillary rheometer was used to observed melt flow behavior. ABS filament exposed to wet condition showed the highest viscosity (ranged between 52.6 to 258 Pa•s) while ABS filament exposed to dry condition showed the lowest viscosity (ranged between 49.65 to 212 Pa•s). Based on simulations on FLUENT, temperature profiles remained constant throughout the liquefier. Viscosity decreases as with increase of shear stress, agreeing to the data from rheometry experiment. In summary, moisture causes degradation of ABS to the extent that it becomes unfit for use in RP due to decrease in thermal and rheological properties.

Chapter 1: Introduction

In this work, a study on the effects of moisture on the Acrylonitrile Butadiene Styrene (ABS) filament material for Fused Deposition Modeling Rapid Prototyping is conducted. Investigation of the bonding behavior and melt flow behavior of the material in the FDM 3000 liquefier is also described. Finite element model of the melt flow channel is generated in FLUENT software. Experiments will be carried out to measure the moisture level of ABS when exposed to different humidity level which will be used to investigate the melt flow behavior and bonding behavior. The FEA gives the result of pressure drop, velocity and temperature profile of the ABS along the melt flow channel.

1.1 Rapid Prototyping

Before studying further into the fused deposition modeling (FDM), which is one of the types of rapid prototyping systems, one must be familiar with rapid prototyping itself. Being in the 21st century, rapid prototyping (RP) has become one of the fastest growing manufacturing technologies for fabrication of cost effective models, prototypes and parts ready to be used in commercial products [1-3]. This technology has been dated back to 1988 with the emergence of the first RP system, stereo lithography apparatus (SLA). It is a family of fabrication methods to make engineering prototypes in minimum possible lead times based on a computer aided design (CAD) model of an item. Before there was rapid prototyping, machining was used to fabricate parts which require long lead times which could lasts up to weeks or more. Hence, with rapid prototyping, parts are able to be produced in hours or days rather than weeks which shorten production time.

1.2 Physical and Virtual Prototyping

Rapid prototyping technologies came to due to the motivation of needing to have a physical model of a new part or product design rather than a computer model or drawing. Due to the lack of ability to visualize the part from a virtual prototype, the technology came to arise. An increased competition in an increasingly fast changing and customized product demand environment has also boosted the use for this rapid prototyping technology.

There are two ways of creating a prototype. One is by physical rapid prototyping and the other one is by virtual prototyping. The basic categories of rapid prototyping involve material removal processes and material addition processes [4]. Material removal RP alternative involves machining and a usage of a dedicated computer numerical control (CNC) machine that is available to the design department in short notice. Primarily, milling and drilling uses this kind of technology in designing and producing parts. Material addition process signifies a new era of three dimensional physical model fabrications. The additive rapid prototyping processes are also termed as ‘layered manufacturing’ process. Material additive process generates less waste compared to material removal process as materials are added layer by layer instead of removing it layer by layer. Hence, this process is much preferred than material removal process when used to produce prototypes. A more detailed study on the types of RP systems will be discussed later in Chapter 2 (Section 2.2).

1.3 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is used to turn computer-aided-design (CAD) geometry into models that can be used for design view, manufacturability studies, investment casting pattern and marketing. In this study, FDM 3000 manufactured by Stratasys Incorporated is used. Figure 1.1 below shows the FDM 3000 made by Stratasys Incorporated.

Figure 1.1: Fused Deposition Modeling machine FDM3000 manufactured by Stratasys Incorporated

1.3.1 ABS material on FDM machine

ABS filament is the core material for all FDM-based machines. It is a durable ‘engineering grade’ plastic which has gained Stratasys company and its machines a reputation for being able to produce some of the most hardwearing prototypes available [5]. This amorphous thermoplastic is usually used in FDM as an application for concept models, form-fit function, snap-fits or vacuum metallization due to its hardwearing nature of the material and the final product accuracy that can be achieved when using this material. Amorphous or also known as non-crystalline is a characteristic where the polymer lacks the long-range order characteristics of a crystalline structure. Due to its reproducibility of the feature details, this plastic can also be used as basis for post-build processes such as electroplating, investment casting and as masters for vacuum casting and forming.

ABS has a default standard color of white but there are also other colors available for special needs. Alongside with this material, the company also produces another derivative, which is the ABSi. It has the same properties as the standard ABS but with a finer feature detail, smoother finish and a semi-translucent appearance. Figure 1.2 below shows a chemical structure of the ABS. There are also blends of ABS such as PC-ABS (polycarbonate-ABS) that combines the strength of a PC and the flexibility of the ABS.

Figure 1.2: Chemical structure of ABS

1.4 Past related works

There were very limited past works that discussed on the effects of moisture on the ABS although there are a number that discussed the ABS used in FDM and their composite properties applied in the machine. There were several users' experiences [61] indicate frequent machine failure to FDM liquefier where ABS material properties play a vital role contributing to the failure. No work has been done to study the effects of moisture on ABS properties which contributed to changes in FDM liquefier. A more detailed discussion on past works will be discussed further in Chapter 2.

1.5 Contribution of this research

This research may be useful for those who are in need of data to use as a basis for maintaining the FDM 3000 machine particularly students and people who own these machine. Researchers and users of the FDM machine can also use the data as a basis for further research. This research may also be used to have a basic understanding on how material storage and its environment may affect the parameters in FDM 3000 machine. ABS has the ability absorb moisture from its surroundings as mentioned earlier in the thesis. ABS has a saturation point of 0.2% and it can only have 1.18% increase in diameter before the filament can no more be used in the liquefier. As mentioned earlier, the allowable filament dimension that can be used in the FDM liquefier is 1.78 mm to 1.80 mm in diameter.

By conducting this research, one is able to uncover the cause of FDM machine head problem and identify the root cause to material degradation of ABS due to moisture absorption. Many users are unaware of such problems which have caused them to make wrong maintenance and repair decision. This leads to costly repairs and maintenance fees. This work reveals the mechanism on how moisture affects ABS properties. With this knowledge at hand, one can apply this work on other application such as the use of ABS polymer in the injection molding application, stereolithography (STL), 3D printer application and such other rapid prototyping application that uses ABS as one of the material to fabricate any desired object. Therefore this research contributes to those who are in need to fabricate a prototype or even ready-to-use manufactured parts as a preliminary data to setting up for parameters to achieve their desired manufactured objects.

1.6 Objectives of the research

To determine the role of moisture in ABS property degradation, several objectives need to be achieved. By achieving these objectives only that one would be able to solely determine the role of moisture in ABS property degradation. Below explains the objectives of the research.

1) To study the effect of moisture absorption on ABS material swelling after exposure at ambient condition and in controlled environments.

Although previous research stated that moisture might not have interfered with FDM machine process, it was observed that ABS filament undergoes changes when exposed for a prolonged time under certain environmental conditions. By changing the properties of the ABS, it can be assumed that these changes may contribute to FDM machine downtime when the exposed material is used. Hence, proving that moisture from surrounding environment affects the ABS especially its properties and behavior becomes one of the goals in the research. By proving that there are effects due to moisture, the researcher will be able to relate the connection between moisture in ABS and how it contributes to FDM machine downtime.

2) To study the physical, chemical, and thermal behavior by means of analysis and relate the effects to FDM machine.

In terms of experimental data, the physical changes of ABS due to moisture will be discussed. The physical change in ABS includes the diameter of the material and the weight of the material. These discussions later relates to latter objectives on proving that moisture affects thermal behavior and chemical structure of ABS filament. Such relationships are important to be discussed as physical changes in ABS might have contributed to the quality of extruded ABS parts and also the FDM machine itself.

3) To model the effects of moisture on melt behavior.

In order to prove that there are changes observed due to moisture absorption in ABS, heat distribution simulation in the FDM liquefier is essential. Hence, the research is conducted such that behaviors obtained from experimental results can be applied in the simulation thus simulate what really happens in the liquefier when moisture is subjected in ABS (the common material used in FDM).

4) To establish a guideline for machine handling of ABS spool material for FDM 3000 so that its shelf life is prolonged

The results of this work will be a guideline on the condition to store and protect the ideal ABS from moisture, thus enable its use for longer shelf life.

1.7 Thesis Organization

This thesis is basically divided into 5 major parts i.e. Chapter 1, 2, 3, 4 and 5. Chapter 1 discusses a general overview of the research. The chapter discusses on rapid prototyping and its current issues particularly in Fused Deposition Modeling. The working principle of the FDM is also discussed in this chapter. Chapter 2 discusses on the literatures related to the research. Any formulas and finding related to the research will be discussed particularly in the chapter. Chapter 3 explains the instrumentation and experimental part of the research. The chapter discusses on how samples are prepared and how the experiments are conducted. The modeling part of the research is also discussed in this chapter. The discussion particularly discussed on how the liquefier was design for the modeling part and the requirements to conduct the model. Chapter 4 discusses the results obtained. All the data obtained will be discussed in this chapter. Additionally, results from simulation model of the liquefier will also be discussed. Chapter 5 summarizes and concludes the research study. Any suggestions on a further study for the research will also be discussed in the chapter.

Chapter 2: Literature Review

2.1 Overview

Chapter 1 has introduced the basic knowledge about the FDM and ABS material. Although basic knowledge of the research is important, a more specific knowledge on the ABS and the FDM is very crucial. This literature review will discuss on the basis of this research which involves many different ideas from FDM and ABS related research. Detailed properties of FDM and ABS are discussed. The concept and ideas on the thermal equations involved in the liquefier, how moisture would affect the ABS in terms of its microstructure and its rheology and bonding and cooling during extrusion are discussed. The first few ideas will involve the bonding quality of ABS and such. As this review progresses, the latter will involve much about the heat transfer within the FDM itself particularly the liquefier. All these ideas will assist the research and provide a better understanding in the research itself. These ideas could also provide strong arguments for the discussion chapter later on.

With this division of sub chapters and depth of these sub chapters, readers will be able to relate the topics to how the objectives and discussion of the research are achieved.

2.2 Types of Rapid Prototyping Systems

Since FDM is the primary RP technology that will be researched and studied, this sub section will emphasize more on the material addition RP technologies. Basically it works by adding layers of material one at a time to build the solid part from bottom to top. Starting materials can be of different kind which includes (1) liquid monomers, (2) powders and (3) solid sheets. To distinguish various material addition RP technologies, its method of building and adding layers to create the solid part is considered. The common approach to prepare the control instructions in all the current material addition RP techniques involves geometric modeling, tessellation of the geometric model and slicing the model into layers. More about types of RP systems will be introduced further in the second chapter.

2.2.1 Liquid based RP systems

Stereolithography (STL or SLA) was the first material addition of RP technology, which dates back to about 1988 and introduced by 3D Systems Inc based on the work of inventor Charles Hull [4,6]. It is a process of fabricating a solid plastic part out of a photosensitive liquid polymer using directed laser bean to solidify the polymer. The general setup is shown in figure 2.1 below.

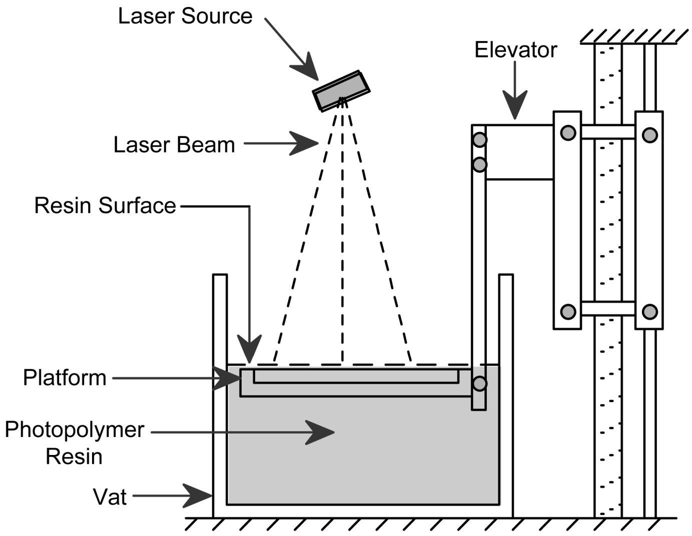

Figure 2.1: General setup of stereolithography

Fabrication of part is accomplished as a series of layers with each layer being added onto one another to gradually build the desired three dimensional geometries. Photopolymers used for STL are typically acrylic although epoxy is also used. The starting materials are liquid monomers which will be polymerized upon exposure to ultraviolet light produced by helium-cadmium or argon ion lasers. Photopolymers are 95% cured after layers being formed. Parts are ‘baked’ in fluorescent oven to completely solidify the polymer and alcohol is used to remove excess polymer. Light sanding is used to improve smoothness and appearance. One of the advantages of stereolithography is its speed in manufacturing parts. There are parts that can be manufactured as shortly as within hours to more than a day depending on the size and complexity of the object. The parts made by stereolithogrpahy are also strong enough to be machined and can be used as master patterns for casting processes. Although parts can be made fast and versatile to be used in machines, the cost to produce these parts is often expensive. Furthermore, as these parts are made by photo-curable resin, often not these parts would experience dimensional instability (shape warping) when exposed to sunlight [3,6].

Solid ground curing (SGC) is similar to STL except that the entire layer is exposed to an ultraviolet light source through a mask that is positioned above the surface of liquid polymer to accomplish the curing of a given layer [4]. Hardening process takes 2 to 3 seconds for each layer. The starting data in SGC is similar to the one used in STL. Solid cubic form created in SGC consists of solid polymer and wax. The wax provide support for fragile and overhanging features of the part during fabrication but it can later be melted away to leave the free standing part. There will be no post curing needed for the completed part which STL needed. With a stable built environment, the possibility curing and warping of the product can be reduced. SGC is also able to produce prototypes with complex geometries and can be done overnight with attended operation (i.e. the build times are predictable). Supports are not required in SGC process. Although there won't be any warping and curling of products, this process needs constant supervision, hence they are labor intensive. There is also an excessive waste of resin and wax. Due to the need of constant supervision, excessive downtimes have been reported [7-8]. Figure 2.2 below shows a setup of a solid ground curing process.

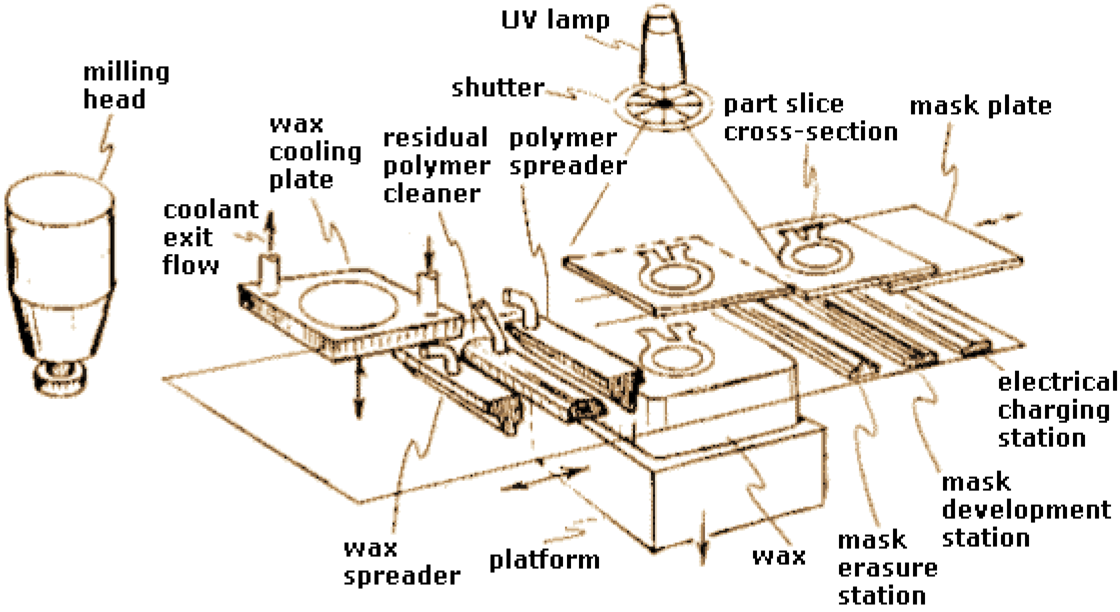

Figure 2.2: Setup of a Solid Ground Curing process

Droplet deposition manufacturing (DDM) operates by melting the starting material and shooting small droplets onto a previously formed layer [4]. A new layer is formed by cold welding the liquid droplets onto the surface. Similar to other RP systems described before, the deposition of droplets for each new layer is controlled by moving x-y spray nozzle workhead whose path is based on a cross section of a

CAD geometric model that has been sliced into layers. Although several commercial RP systems are based on this general operating principle, the types of material deposited and the corresponding technique by which the workhead operates to melt and apply the material differentiates the systems. Wax, thermoplastics, and metals with low melting point are used as starting material for this kind of technology. With DDM, products have good dimensional accuracy and surface finish. However, DDM requires more time to build up a prototype. Material selection for this process is also limited to low melting temperature of thermoplastic and wax [9].

2.2.2 Solid based RP systems

Funded by the National Science Foundation, Helisys Inc. was the first company that offered laminated object manufacturing (LOM) systems that was researched and developed before it was shipped in 1991 [4]. LOM produces a solid physical model by staking layers of sheet stock that are each cut to an outline corresponding to the cross sectional shape of a CAD model that has been sliced into layers. Prior to cutting, layers are bonded on top of another while its excess material remains in place to be a support for the part during building. Paper, cellulose, plastic, metals or fiber reinforced materials can be of the system's starting material as long as it is in sheet stock form. When layers are completed, the new part is separated from the excess external material using hammer, putty knife, and wood carving tools. Sealing application is recommended to prevent moisture absorption and damage.

Fused Deposition Modeling (FDM) was developed by Stratasys Inc and sold its first machine in 1990. It is an RP process in which a filament of wax or polymer being extruded onto the existing part surface from a workhead to complete each new layer. More about FDM will be discussed in its individual section (Section 2.5).

2.2.3 Powder based RP systems

Developed by University of Texas (Austin) as an alternative to STL and now currently marketed by DTM Corporation, selective laser sintering (SLS) uses a moving laser beam to sinter heat-fusible powders in areas corresponding to the CAD geometric model one layer at a time to build the solid part [4]. A new layer of loose powders is spread across the surface using a counter rotating roller after each layer is completed. To facilitate bonding and reduce distortion, the powders are preheated to just below their melting point. Contrary to STL, SLS has a more versatile process in terms of possible work materials. Polyvinylchloride, polycarbonate, polyester, polyurethane, ABS, nylon, and investment casting wax are the current materials used for SLS. These materials are less expensive than the resins used in SLA. Metals and ceramic powders are also being used in SLS.

Three dimensional printing (3DP) technology was developed at Massachusetts Institute of Technology in which it builds a part in the usual layer by layer fashion using an ink jet printer to eject adhesive bonding material to successive layers of powders [4]. The binders hold the powders to form a solid part while the unbonded powders remained loose to be removed later. The loose powder provides support for overhanging and fragile features of the part. When build process is completed, the part is heat treated to strengthen the bond and remove the loose powders. Powders of ceramic, metal, or cermet are used as starting materials in 3DP. For binders, binders that are polymeric or colloidal silica or silicon carbide are used.

2.2.4 Virtual Rapid Prototyping

Another technique in the process of product development is virtual prototyping. This process involves computer-aided design (CAD) and computer-aided engineering (CAE) software to validate a design before committing to make a physical prototype [10-11]. A computer generated geometrical shapes for the parts is created and later combined into an ‘assembly’. After combined into an assembly, different mechanical motion, fit and function are applied to the prototype. The assembly may also be an aesthetic appeal to the whole ensemble. These assemblies or individual parts could be opened using CAE software to simulate the behavior of the product in the real world.

By using virtual prototyping, engineers and scientist can design, optimize, validate and visualize their products digitally and evaluate different design concepts before incurring the cost of physical prototypes. Realistic machine operations can be visualized, estimating cycle time throughput, determine whether the product will fail and glean important information about the dynamic behavior of the design. With virtual prototyping, alternatives to design to improve prototype performance and design quality can be done without investing as much time and money required building physical prototypes.

2.3 Applications of RP

Rapid prototyping is being applied in a vast number of fields such as aerospace, automotives, architecture, and medicine. Its application can be classified into three major categories including design, engineering analysis and tooling and manufacturing.

Design is the initial application of RP as designers are able to confirm their design by building a real physical model in minimum time using rapid prototyping. Instead of communicating by paper drawing or displays on CAD system monitor, the functions and features of the part can be properly understood with the availability of RP systems. With reduced product development cycle time, product can be distributed into the market faster hence benefitting the manufacturers.

Without a physical entity, certain types of engineering analysis and planning activities may have not been able to be accomplished. Hence the existence of RP fabricated part allows these analyses to be conducted. In such circumstances where engineers and scientists has to simulate difficult situations (i.e. hazardous environments, bridges, aeroplanes) where physical rapid prototyping is not possible, virtual rapid prototyping provides an alternative to simulating and analyzing these products.

It has become a trend in the RP applications to become a greater use in the fabrication of production tooling and in the actual manufacture of parts [3]. The term rapid tool making (RTM) is used to distinguish this RP adaption in fabricating production tooling. RTM applications is divided into two approaches i.e. indirect

RTM method in which pattern is created by RP and the pattern is used to fabricate tools and direct RTM method in which RP is applied to fabricate the tool itself. Other areas that apply rapid prototyping technology include arts and archeology. Complex art sculptures can be made through rapid prototyping. Precious historical artifacts (i.e. ancient sculptures, bones) can also be prototyped/duplicated with rapid prototyping technology. Although RP is moving towards this trend, it can be said that not all RP technologies can be used for this application due to limited product accuracy, short tooling life (in such circumstances where parts produced from rapid prototyping are used directly in machineries and products) and material mismatch (different product material).

2.4 Advantages and disadvantages of RP systems

Designs attributed to RP could reduce lead time to produce prototype components and improve a designer ability to visualize the part geometry based on its physical existence. With the ability to visualize part geometry, earlier detection and reduction of design errors can be accomplished. Engineers and scientists alike will also be increasingly capable to compute mass properties of components and assemblies. As said earlier, by reducing product development lead time, the time to market of these products can be reduced.

It can be said that being able to compute these properties become a factor to engineering analysis and planning activities to be accomplished. Comparison of different shapes and styles to optimize aesthetic appeal can be done with the existence of RP parts. The analysis of fluid flow, wind tunnel test, stress analysis and fabrication of preproduction parts can all be done with the existence of these RP parts.

Even though the existing of rapid prototyping technology has only been around for 23 years [14], this technology is rapidly advanced with several known issues with it. Part accuracy, limited variety of material and mechanical performance of fabricated parts become the principal problems with the current RP technology.

Mathematically, process related and material related issues become part of the reasons that these products could not achieve the derived accuracy. Mathematical errors that contribute to part accuracy include approximations of parts surfaces used in RP data preparation and the differences between the slicing thickness and the actual layer thicknesses in the physical part which will cause z-axis dimensional errors [12-13]. With an increased layer thickness, staircase effect becomes more apparent for a sloping part surface hence becomes an inherent limitation to the produced part. Manufacturing industry that uses RP system results in process related errors. The errors degrade each shape of each layer as well as the registration between adjacent layers. Consequently, Z-axis dimension can also be affected. Shrinkage and distortion are few of the material related errors occurred in RP technologies. By enlarging the CAD model of the parts based on previous experience with process and material, the allowance for shrinkage can be obtained.

Mismatches in materials and mechanical properties causes prototypes to have different behavior than production parts. Residual stress-driven delamination or debonding between successively deposited isotropic material layers associated with any process involving successive deposition of material layers at elevated temperatures, such as multi-layered films or coatings causes' material mismatch [12]. Residual thermal stresses build up are due to the free thermal contraction of a newly deposited material experiences as it solidifies and cools. This causes delaminations between layers as residual stresses acts as the driving force in the extension of interfacial cracks from the edges of the part towards its center. As delamination propagates, mismatch occurs and hence compromising its mechanical properties and behavior.

Although overall cost reduction in the complete product development cycle is drastically reduced, the cost-per-piece of as-prototyped part is still high. This is due to the high cost in producing the prototyped. As rapid prototyping technology is still new and still developing, reducing the cost to produce prototypes has not been the priority. Hence the cost-per-piece of as-prototyped part is still expensive. Virtual rapid prototyping might reduce the cost for as-prototyped part yet there are limits to what prototypes can be created virtually.

Rapid prototyping technology uses a specific data file format before the machines are able to produce parts or prototypes. Only STL files are allowed for a standard CAD data format. Data derived from other source such as scanned data from a CT scanner, MRI or even 3D laser digitizer has to be converted or reconstructed in 3D CAD format before being transferred into rapid prototyping machine. By converting or reconstructing these data, some detailed information i.e. part geometry, detailed features might be lost causing inaccuracy in the prototype produced.

2.5 Fused Deposition Modeling (FDM)

2.5.1 FDM operating principles

There are basically four main parts in the Stratasys modeling system [15]. They are:

a) Slicing Software

b) Computer Workstation

c) FDM 3000 Modeler

d) Modeling Materials

Before producing a part using the FDM, a CAD file must be created. The CAD file then must be converted to an STL format. The STL file is later read into Stratasys slicing software named Insight. Insight breaks the model into individual slices, with each slice representing one layer of material. The software will then generate tool paths to fill the slices. These tool paths form the SML file. After slicing the STL file and create a Stratasys Modeling Language (SML) file, the SML file is then downloaded to the FDM Hardware for modeling.

In the FDM hardware, the FDM head moves in two horizontal axes across the foundation and deposits a layer of material for each slice. The material is heated by the FDM head so it comes out in a semi-liquid state. The successive layers are then fused together and solidify to build up a product or model of the design. Figure 2.3 shows a zoomed view of the FDM 3000 liquefier.

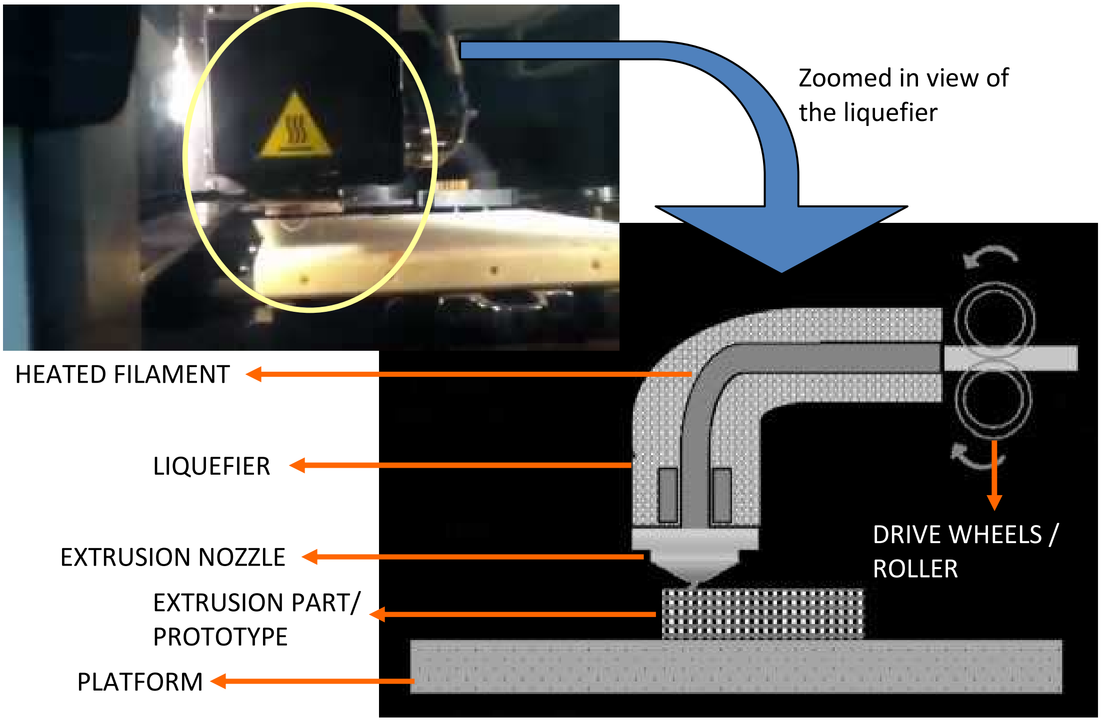

Figure 2.3: Zoomed in view of FDM 3000 liquefier

WaterWorks Soluble Release is one of the features in FDM 3000 [15-16]. With a bench top unit standing forty-five and one half inches high with a 26 x 36 inch footprint, the FDM 3000 would be considered of a smaller size than the latest FDM-s [4]. Since this machine does not require exhaust hood or other special facilities, it can be placed next to the designer's CAD workstation for convenience.

2.5.2 FDM machine parameter

There are several process control parameters that could affect the properties of FDM parts [17]. They are listed as follows.

- **Bead (or road) width:** This is defined as the thickness of the bead (or road) that the FDM nozzle deposits. This length can vary from 0.012 inches to 0.040 inches for the T12 nozzle installed on the FDM machine. One should bear in mind that for this particular nozzle, the bead width is of previous stated dimension. A different type of nozzle (T10 or T16) will result a different bead width.

- **Air Gap:** This is the space between the beads of FDM material. The default value is zero which means that the beads touch each other. This space can be modified to leave a positive gap so that the beads of the material would not touch. A non-zero air gap would result is a loosely packed structure that builds rapidly. A negative gap can also be specified which leaves the beads to occupy the same space. This results a closely packed structure with a longer build time. This parameter also has a large influence on the bonding between roads within and between layers and on the resulting material density.
- **Model Build Temperature (or Liquefier Temperature):** This is the temperature of the heating element for the model material. This temperature controls how mechanical properties of the material are or the extrusion flow as it is extruded from the nozzle. The temperature also influences the fiber solidification characteristics and also the molecular diffusion bonding process between the filaments. For FDM process, this is a critical parameter which requires correct setting for a given build material properties.
- **Raster orientation:** This is the direction of the beads of material (roads) relative to the loading of the part. This parameter controls the filament layout within and between material layers.
- **Nozzle Speed during Extrusion:** This parameter controls the cross section geometry and volume of the extruded filament.

- **Normalized Extrusion Flow Rate:** This parameter controls the bulk-filament feed speed to the extrusion head. This value corresponds to the filament width which is proportional to the volumetric flow rate.

There are also other parameters such as envelope temperature, increment in nozzle height and interlayer configuration which affects the FDM end product [17]. These parameters are ignored as they affect the end product similar to the parameters mentioned above and are insignificant.

2.5.3 FDM liquefier parameter study

Yardimci study the conceptual framework for the thermal process modeling of fused deposition [19-20]. They examined the rationale behind a cooling process model. This is important on a need to know basis as cooling process allows the semi molten material to bond to each other diffusively. The thermal energy absorbed by the building material during heating and extrusion is the drive to this bonding. Severing the structural stability of a part produced during fused deposition may have been caused by premature cooling. Premature cooling reduces total residence below prespecified value of thermal energy resulting insufficient bonding hence severing structural stability [21-22]. Apart from the variation of strengths in the finished part depending on its road interaction model, effect of heat transfer coefficient may be clearly seen by comparing the relative magnitudes of bonding potential. Although this study will not be use extensively as a basis for the research, it is essentially important to know for the study in thermal simulation of FDM liquefier later on.

Nevertheless, the cooling process does play a big role in the structure stability of finished products extruded using FDM.

One may argue if there is a need to understand the mathematical relations of a liquefier dynamics in fused deposition yet they agree on such circumstances that it is essential to understand a part of the mathematical model. Being the centre of fused deposition process extrusion is a process during which the thermoplastic filament is introduced through mechanical pressure into the liquefier then extruded to form desired product. Since the rollers are the only drive mechanism in the material delivery system, filament goes under stress upstream to the roller and under compression downstream acting as a plunger which subsequently becomes the driving force in extrusion process. To overcome the pressure drop across the system, the force required needs to be sufficient enough. This strictly depends on the viscous properties of the melt and also the geometry of the liquefier and nozzle [23]. For this particular research, the geometry of the liquefier and nozzle is set to be constant. Thus the idea of studying effects of moisture of viscous properties of melt affecting the force needed to overcome pressure drop is strictly observed and studied.

As melts adhere to liquefier/die walls, materials are likely to be subjected to shear deformation during the flow. Shear rate calculation is shown in equation (2.1) below. $\dot{\gamma}$ is shear rate and *dv/dr* is the rate of change in velocity with the change in distance.

$$\dot{\gamma} = -\frac{dv}{dr} \tag{2.1}$$